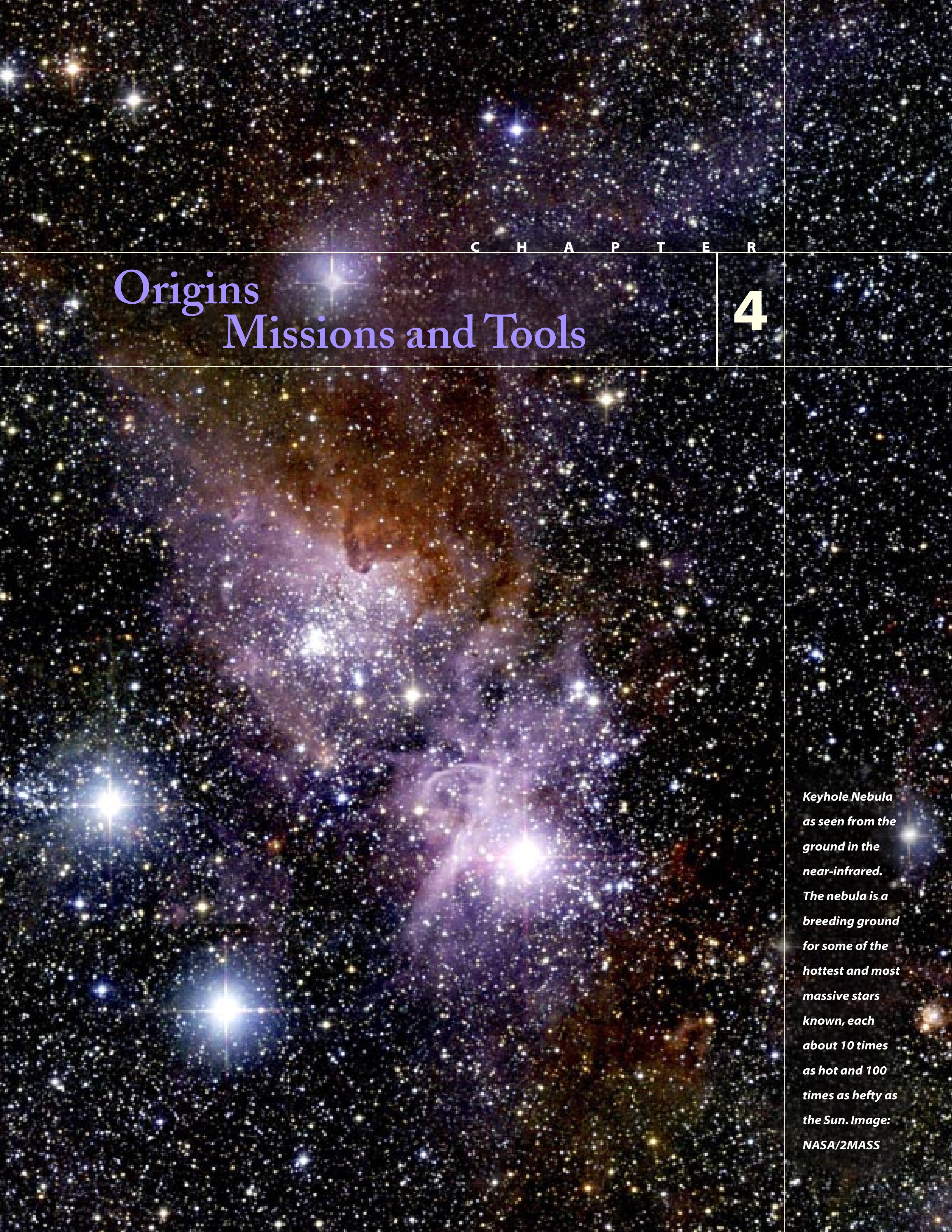
CHAPTER 4

Origins Missions and Tools



Keyhole Nebula as seen from the ground in the near-infrared. The nebula is a breeding ground for some of the hottest and most massive stars known, each about 10 times as hot and 100 times as hefty as the Sun. Image: NASA/2MASS

...to build on the past, and leave a legacy for future missions.

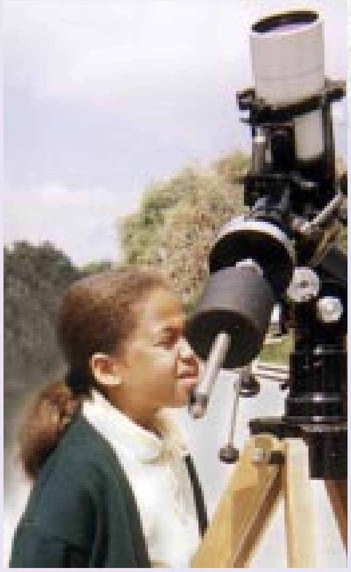
The central principle of the Origins mission architecture has been that each major mission builds on the scientific and technological legacy of previous missions, while providing new capabilities for the future. In this way, the complex challenges of the theme can be achieved with reasonable cost and acceptable risk. For example, the techniques of interferometry developed for the Keck Interferometer, the Large Binocular Telescope Interferometer and the Space Interferometry Mission, along with the infrared detector technology from the Space Infrared Telescope Facility and the large optics technology needed for the James Webb Space Telescope will enable the Terrestrial Planet Finder to search out and characterize habitable planets.

Inspired by bold vision, this philosophy has allowed the Origins theme to navigate through many daunting scientific and technological questions, toward a set of specific scientific missions, and toward scientific goals that stretch even beyond the missions we now know how to define. Six years down the path from the first Origins Roadmap, much has been learned about the technological difficulty and the scientific framework for this scientific theme, which brings into play another feature of a robust strategic plan: flexibility and adaptability. Origins has a policy of ensuring that all major technological problems have been solved prior to embarking on the expensive construction phase of its challenging missions. Even so, the challenges to achieving the scientific goals of Origins are so great, that in addition to mission-oriented enabling technology developments, additional options for gaining precursor scientific knowledge through observations from the ground, work in scientific theory, and more modest precursor missions must be added to the future investigative agenda. While the vision remains, the path and the pace must be what the nation will afford.

At the publication of the *Origins 2000 Roadmap*, less than half the extrasolar planets now known had been discovered. Today, we see increasing pace of discovery through ground observations of radial velocity Doppler shifts and photometric transits as data sets are filled in. Technology development and mission architecture studies conducted in the previous decade did not suggest that large single-aperture visible-light coronagraphs would be viable for a terrestrial planet finding mission. Today, Terrestrial Planet Finder (TPF) architecture studies and technology development do include coronagraphs, and also precursor mission options of reduced scope. The recently selected Kepler mission in the Discovery Program will provide valuable planetary system statistics, and exemplifies the kind of alternate approaches Origins must embrace. The dynamic state of this emergent scientific field suggests strongly that the program undertaken to achieve the Origins goals must remain flexible, and must adapt to and make use of evolving technical and scientific knowledge and capability. The Origins roadmap for 2003 elaborates on the previous plan, adding "off-ramps" from some endeavors that may prove too difficult

Girls Inspired to Imagine New Worlds

A few hundred participants and their families gathered in May 2002 at Pasadena City College to learn about Origins science and celebrate the winners of the "Imagine a New World" art and essay contests, sponsored by Girls Inc. and NASA's Navigator Program.



Taking an interdisciplinary approach, the contests were provided through the Operation SMART program, an age-appropriate curriculum that builds girls' skills in math, science, and technology. Co-sponsor Girls Inc. is a national nonprofit youth organization dedicated to inspiring all girls to be strong, smart, and bold.

Elementary and middle school-age girls in the Los Angeles area were asked to imagine life on a distant planet, using Navigator educational materials as background. A diverse panel of judges graded the entries based on creativity, literacy, and incorporation of Navigator themes.

The contest was capped off with a celebration at which the winners were presented with awards and certificates. All participants were treated to a half-day of fun learning activities, including "Ask a Scientist," "Taking the Measure of the Universe," and planetarium tours.

or too costly to maintain, and finding "alternate routes" to arrive at the same objectives, while reflecting realistic assessments of the cost and risk inherent in scientific discovery and exploration.

Origins will solicit new ideas for technology developments and scientific missions of moderate scale that hold promise for facilitating the Origins goals. Solicitations through NASA Research Announcements will provide a science and technology incubator to obtain and support proposals for technology development and mission concept definition studies. The most promising of these may be pursued as possible flight missions through the Explorer or Discovery Programs or even a future competed mid-size Origins mission program. Complementing the missions described below, the Research and Analysis (R&A) program provides three essential components of the Origins theme: (1) development of key technologies that will be necessary for Origins missions; (2) development of alternate mission concepts which could lead to smaller-scale intermediate missions exploring aspects of the Origins scientific agenda; and (3) a broad program of scientific theory and analysis that helps frame the scientific questions, provides models to define the science requirements for key missions, and is critical for the understanding of the vast amounts of data expected from space missions in the coming decade. Increasingly, the development of strategic missions will invoke, and fund, targeted application of R&A programs to help draw in a broad constituency in developing new scientific knowledge and technology. The Origins R&A program is described in Chapter 6.

Even as we work to develop the missions for this and the next decade, we must start now to envision where our explorations will lead us afterwards, as developing the needed technologies can easily take a decade or more before they are ready to be applied. Our focus will be placed not on specific missions, but on the compelling scientific questions and the technologies that will enable the missions and tools to find the answers. Beyond TPF, scientific attention will turn to detailed studies of any indications of life found on the planets that TPF discovers. This will require a still more capable spectroscopic mission, a Life Finder (LF), which will probe the infrared spectrum with great sensitivity and resolution. Both Origins and the Structure and Evolution of the Universe Theme call for advanced investigations in galaxy and planetary system formation and cosmology that require a high resolution IR telescope such as the Single Aperture Far-Infrared Observatory (SAFIR), an 8-meter space-based telescope recommended in the National Research Council decadal survey. Such a telescope might launch and operate between TPF and LF to carry out its own science program, and to lead to the 25-meter telescopes needed for LF. The technology developed for such a mission might also be used as a building block for a kilometer-baseline interferometer used at far-infrared wavelengths for cosmological studies. Investigations in distribution of matter in the universe (including dark matter) will require a large-scale UV/optical observatory that will build on the technology developments of the James Webb Space Telescope (JWST) and of the Space Interferometry Mission (SIM), and pave the way for more challenging UV/optical telescopes of the future. The technology developments necessary to enable these missions are described in Chapter 5, Enabling Technologies.

While the Astronomical Search for Origins and Planetary Systems remains inspired by a far reaching vision, the rules of the road will be those of clearly focused waypoints and sound management practices.

Operational Missions

Foremost among the current Origins missions is the Hubble Space Telescope (HST), which was launched in April 1990, and—thanks to regular upgrades of its instruments via Shuttle servicing missions—remains NASA's most productive scientific program. This impressive record of achievement continued into the second decade of HST's operation, with the installation in early 2002 of the Advanced Camera for Surveys (ACS) and a new active cooling system to reactivate the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The subsequent and probably final Shuttle servicing mission, planned for 2004, will install both the highest performance ultraviolet spectrograph ever flown in space, the Cosmic Origins Spectrograph (COS), as well as the first truly panchromatic imaging system ever flown in space, the Wide-Field Camera 3 (WFC 3). This mission will also install a number of engineering system replacements to enable the observatory to operate through 2010, at which time it is planned to retrieve the telescope in the Space Shuttle.

The importance of HST to the scientific community is matched by the positive role that the mission has played in educating the public about science. The observatory may be the best-known scientific facility in the world, with its results used in classrooms globally.

The most recent Origins mission to be launched is the Far-Ultraviolet Spectroscopic Explorer (FUSE), which explores the universe at wavelengths that are inaccessible by HST. In particular, FUSE is determining the abundance of deuterium, an isotope of hydrogen that was formed in the Big Bang. Determination of its abundance is essential to constraining conditions in the Big Bang. Beyond this, FUSE will also investigate the hot interstellar gas, in order to understand the life cycle of matter between the stars, as gas cycles between stellar death and rebirth. A highlight of the education and public outreach program of the FUSE mission is its highly visible role in the Maryland Science Center, in Baltimore, which is visited by over 600,000 persons per year.

The Space Infrared Telescope Facility will contribute extensively to the understanding of the formation of stars and planets and will investigate the formation and early evolution of galaxies.

Ground Observatories

The Origins theme supports a broad science program in conjunction with the W.M. Keck Observatory in Hawaii. This program has two main thrust areas: first the sponsorship of community-accessible time on single Keck telescopes to pursue Origins science goals; and second, the development and operations of the Keck Interferometer (KI). The single-Keck program has been in place since 1996, and has been extremely successful in producing important scientific results such as radial velocity exo-planet detections, spectral characterizations of L and T-dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-meter Keck telescopes to undertake a variety of Origins astrophysical investigations. Among the issues addressed by KI will be the location and amount of zodiacal dust in other planetary systems and the astrometric detection and characterization of exo-planetary systems around stars in the solar neighborhood. This first in-depth and long-term census of planets will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define the requirements and the architecture for TPF.

The Large Binocular Telescope Interferometer (LBTI) will further a variety of Origins goals in

The Stratospheric Observatory for Infrared Astronomy, flying on a modified Boeing 747 aircraft, will study sites of star formation, the cold interstellar medium, and the center of our galaxy at high spatial resolution.

star, planet, and galaxy formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-meter LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to filled aperture telescopes. This is applicable to a wide variety of Origins-related imaging and astrometric observations.

The National Virtual Observatory (NVO) will build on developments in computing and information technology and will have a major impact on Origins missions and science. For the most part, essential technologies will emerge from academia and industry and will be usable without Origins-specific development initiatives. The NVO will federate digital sky surveys, observatory and mission archives, and astronomy data and literature services, and provide a framework that will reduce the cost of developing and maintaining future archives and data services. The NVO will be able to address research topics of particular relevance to the Origins program, such as:

- Star formation rates in galaxies
- The environments of clusters of galaxies, e.g, through systematic searches for gravitational lenses
- The galaxy merger rate as a function of look-back time
- The population of brown dwarfs, through cross-correlation of survey catalogs
- Cosmological models, through confrontation of simulations with observations
- A complete census of Kuiper-Belt objects, and a compositional atlas of the solar system, as a means to understanding the formation process and dynamics of the solar system

The NVO will also be an unprecedented venue for science and technology education and public outreach.

Missions Targeted for Operation by 2005

The Space Infrared Telescope Facility (SIRTF) will be the fourth of NASA's Great Observatories and will use imaging and spectroscopy at infrared wavelengths from 3–180 micrometers to investigate Origins scientific goals. In particular, SIRTF will contribute extensively to the understanding of the formation of stars and planets and will investigate the formation and early evolution of galaxies. SIRTF will provide key information on the dust environments TPF will need to penetrate to find and characterize planets. A very important component of SIRTF science will be the Legacy Programs, in which very large and scientifically important data sets will be made available rapidly to the entire scientific community. Six teams with broad community participation have been competitively selected to execute Legacy Programs. SIRTF is a cryogenic mission with an expected cryogenic lifetime of up to 5 years. The wide applicability of infrared technology is highlighted in the mission's extensive eduction and public outreach program.

The Stratospheric Observatory for Infrared Astronomy (SOFIA) will study sites of star formation, the cold interstellar medium, and the center of our galaxy at high spatial resolution at far-infrared wavelengths. It is a joint U.S. (80%) and German (20%) observatory which consists of a 747 aircraft with a telescope as large as HST. SOFIA will also function as a unique platform for developing, testing, and reducing risk of new instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, including involving high school teachers and students in its flights and observations. SOFIA will be making observations by 2005.

The Kepler mission will complete a photometric survey of the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone.

Missions Targeted to Enter Development Phase in 2005–2010

Extrasolar planets are a reality: more than one hundred planet-sized objects have been indirectly detected around neighboring stars and their number is growing rapidly. But the techniques available from the ground today are capable of detecting only the most massive such objects, perhaps a few times the mass of Saturn. The Keck Interferometer will push this mass limit significantly lower, possibly to the mass of Neptune. However, it will require space-based techniques to detect objects that approach the mass of Earth and allow the first in-depth search for objects in space like our own home planet.

Kepler is a new mission in the Origins firmament, selected through the Discovery Program and scheduled for launch in 2007. This provides an excellent example of the kind of moderate scale missions that can contribute to Origins in important ways. The Kepler mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets.

The Space Interferometry Mission will be the first observatory capable of detecting and measuring

The Space Interferometry Mission will extend the Keck census of nearby planetary systems into the range of rocky, terrestrial planets.

the mass of planetary bodies with a few times the mass of Earth in orbit around nearby stars. Thus, the Origins theme will take a major step forward in answering one of its defining questions: "Are we alone?" Are there other worlds like our own home planet, existing within planetary systems like our own solar system? SIM will extend the Keck census of nearby planetary systems into the range of the rocky, terrestrial planets for the first time, permitting scientists to refine their theories of the formation and evolution of planets like Earth. This census will form the core of the observing programs for subsequent missions that will investigate in detail the nature of these newly discovered worlds. It will provide the "target list" for TPF.

In addition to its scientific goals, SIM will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

SIM Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Interferometric techniques	Keck Interferometer	TPF (interferometer options), Life Finder, Far-IR Interferometer
Nanometer stabilization techniques	HST, Chandra	TPF, SAFIR, Large UV/Optical Telescope, Life Finder
Picometer sensing techniques	New	TPF, Life Finder

Beyond the detection of planets, SIM's extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy. This will permit studies of the dynamics and evolution of stars and star clusters in our galaxy in order to better understand how our galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators enabling us to improve our understanding of stellar processes and to measure precise distances throughout the universe.

The next step beyond the Hubble Space Telescope will be the James Webb Space Telescope,

JWST Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	SIRTF for passive cooling	TPF, Life Finder, Large UV/Optical Telescope, SAFIR
Cryogenic coolers	HST-NICMOS, Planck, TPF Technology	SAFIR, Life Finder
IR detectors	SIRTF, SOFIA	TPF, SAFIR

Each Origins mission builds on the scientific and technological legacy of the previous mission, while providing new capabilities for the future.

which will have three times the diameter of HST's mirror and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the universe causes the light from very young galaxies to appear most prominently. JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a very wide range of astronomical questions, including those that are central to the Origins theme.

JWST is expected to have a telescope diameter of at least 6 meters and be celestial-background-limited between 0.6 and 10 micrometers, with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 micrometers. With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

The European Space Agency and the Canadian Space Agency have agreed to contribute significantly to the JWST project. These contributions will be important in significantly enhancing the overall capabilities of the observatory.

Missions Targeted to Enter Development Phase in 2010–2015

The Terrestrial Planet Finder will directly detect and study planets outside our solar system from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant solar systems as well as their gas giant companions. In addition, TPF spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including gas giants, terrestrial planets and debris disks. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.

TPF Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	JWST	SAFIR, Life Finder
Formation flying	StarLight ground demo	LISA, Far-IR Interferometer, Life Finder
Interferometry and nulling	SIM, LBTI, Keck Interferometer	Far-IR Interferometer, Life Finder
IR detectors and cryocoolers	JWST, Planck	SAFIR, Far-IR Interferometer, Life Finder
Coronagraph	Precursor mid-size mission	Future filled-aperture observatories

The TPF observatory will likely take the form of either a coronagraph operating at visible wavelengths or a large-baseline interferometer operating in the infrared. The visible-light coronagraph concepts would use a single telescope with an effective diameter of 8–10 meters, operating at room temperature, but required to achieve a billion-to-one

The James Webb Space Telescope will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a wide range of astronomical questions.

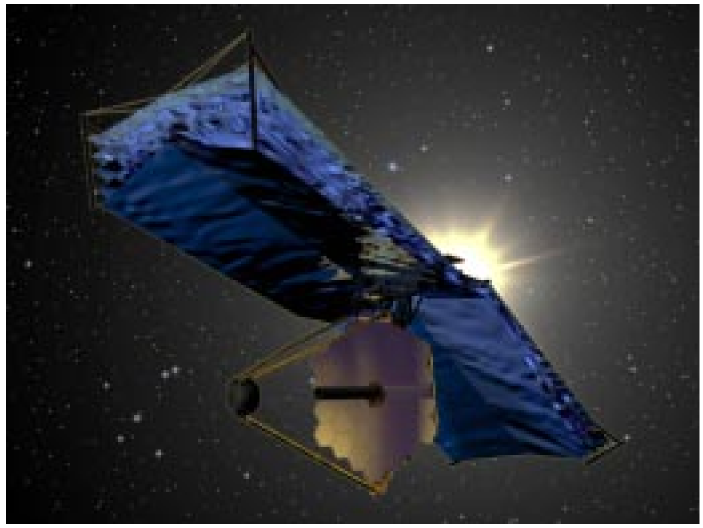


image contrast. Very precise, stable control of the telescope optical quality would be required. The infrared interferometer concepts would use multiple (≈4), smaller, 3–4-meter-diameter telescopes configured as an array and spread out over a large boom of up to 40 meters or operated on separated spacecraft over distances of a few hundred meters. The telescopes would operate at extremely low temperatures of ≈40 kelvin, and the observatory would necessarily be large. However, the image contrast requirement, "only" a million to one, and thus the required system optical quality, would be much easier to achieve at infrared wavelengths.

TPF will perform system studies, science investigations, and technology development for both architecture classes over the next several years. Final selection of a TPF architecture will occur about 2006, based on the science and technology progress of the next four years. Also, multimission architectures that take smaller steps toward the ultimate scientific goal will be investigated.

The European Space Agency (ESA) has been actively studying an infrared interferometer with essentially the same science goals as TPF, usually referred to as either Darwin or the Infrared Space Interferometer (IRSI). Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.

Missions Targeted to Enter Development Phase in 2015–2020

A long-term Origins goal is the detailed study of life and its evolution in ecosystems beyond the solar system. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of ~1,000, utilizing a version of TPF with 25-meter telescopes. While a Life Finder interferometer is beyond the horizon of this strategic plan, except as a beacon for the technologists' vision, the Single Aperture Far-Infrared mission consisting of a single 8–10-meter telescope operating in the far-IR could serve as a building block for the Life Finder while carrying out a broad range of scientific programs beyond JWST and SIRTF. These include probing the epoch of energetic star formation in the redshift range $1<z<10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-

SAFIR Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	JWST, TPF	Life Finder
IR detectors and cryocoolers	JWST, Herschel, Planck, TPF	Life Finder, Far-IR Interferometer

enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, OI, NII; learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and, studying the nature of the recently discovered objects in the Kuiper Belt of our own solar system which may be remnants of our own planet formation process.

Large UV/Optical Telescope Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large optics	JWST, Coronagraphic TPF	Visible light complement to Life Finder
UV detectors	HST, FUSE, Galex	

A successor to HST operating at ultraviolet and optical wavelengths, a large UV/optical telescope, would produce forefront science in all areas of modern astronomy and would be focused on the era from redshifts, $0<z<3$, which occupies over 80% of cosmic time, beginning after the first galaxies, quasars, and stars emerged into their present form. The science to be addressed in the post-HST era includes studies of dark matter and baryons, the origin and evolution of the elements, and the major construction phase of galaxies and quasars. Key questions include: Where is the rest of the unseen universe? What is the interplay of the dark and luminous universe? How did the intergalactic medium collapse to form the galaxies and clusters? When were galaxies, clusters, and stellar populations assembled into their current form? What is the history of star formation and chemical evolution? Are massive black holes a natural part of most galaxies? A large-aperture UV/optical telescope in space will provide a major facility in the second quarter of the century for solving these scientific problems.

The Far Future: Beyond 2020

Two missions still far in the future because of their demanding technologies have strong relevance to Origins goals. The first is the Life Finder, which as described above would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth.

A second mission concept that appears promising is an interferometer capable of detecting the far infrared and submillimeter light from the youngest galaxies. JWST will study the visible starlight from forming galaxies that has been red-shifted into the near infrared by the expansion of the universe. However, typically half, and sometimes more than 99% of the starlight of a galaxy is absorbed by dust in that galaxy and re-radiated in the far infrared. This emission is red-shifted further into infrared or into the submillimeter bands. An interferometer consisting of three 15–25-meter telescopes with a 1-kilometer baseline would have the sensitivity and angular resolution (0.02 arcseconds at 100 micrometers) needed to study the physical conditions in these young galaxies. In addition to cosmological studies, the interferometer would be able to observe collapsing protostars deeply embedded in their parental molecular clouds, providing valuable constraints on models for star formation.